CONFUSION OF EXTRAGALACTIC SOURCES IN THE MID- AND FAR-INFRARED: *SPITZER* AND BEYOND

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ABSTRACT

We use the source counts measured with the Multiband Imaging Photometer for *Spitzer* (MIPS) at 24, 70, and 160 μm to determine the 5-σ confusion limits due to extragalactic sources: 56μJy, 3.2 and 40 mJy at 24, 70 and 160 μm, respectively. We also make predictions for confusion limits for a number of proposed far infrared missions of larger aperture (3.5 to 10m diameter).

Subject headings: infrared: galaxies – galaxies: evolution – galaxies: statistics

1. INTRODUCTION

In addition to detector/photon noise, cosmological surveys in the far-infrared (FIR) spectral range are limited in depth by: 1.) structure in the infrared cirrus emission; and 2.) confusion by extragalactic sources. The first of these limitations can be avoided for some programs by observing in particularly low-background regions on the sky The second limitation arises because the high density of faint (resolved or unresolved) distant galaxies creates signal fluctuations in the telescope beam (Condon 1974; Franceschini et al. 1989; Helou & Beichman 1990; Rieke et al. 1995; Dole et al. 2003; Takeuchi & Ishii 2004, for instance). Because distant galaxies are distributed roughly isotropically and with a high density compared to the beam size, this noise is unavoidable.

Extragalactic confusion noise can be robustly estimated by measurements of source counts combined with modeling to extend the counts to faint levels. We use new determinations of number counts in the three Multiband Imaging Photometer for *Spitzer* (MIPS, Rieke et al., 2004) bands, 24, 70, and 160 μm (Dole et al. 2004; Papovich et al. 2004), and a model fitting all those observables (Lagache et al. 2004) to determine more accurate limits for extragalactic confusion than have been available previously. Extragalactic confusion noise does not strictly follow Gaussian statistics. Therefore, we discuss confusion limits in four different ways that are appropriate to various measurement situations: the photometric criterion and source density criterion (hereafter SDC) (Dole et al. 2003), and the levels deduced from the source densities of one source per 20 and 40 independent beams. We parameterize the noise as a "5 − σ" limit calculated as if it were Gaussian, because it is difficult to derive any other simple metric. All the definitions and values relative to MIPS *Spitzer* beams are summarized in Table 1 of Dole et al. (2003).

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We summarize the confusion limits for *Spitzer* in its three far-infrared bands in Table 1. The situation is different at 24 and 70 μm than at 160 μm. In the two first bands, where the background is resolved to a significant extent, the confusion mainly results from the high density of resolved sources and their interference with extraction of fainter ones: the SDC is the appropriate measure (and the classical photometric criterion underestimates the confusion level). In the third band, where the background is not well resolved, the confusion results from a population fainter than the sensitivity limit. In the latter case, confusion (and CIB fluctuation) properties are directly linked to galaxy populations not directly detectable but which modulate the background level: the photometric criterion is appropriate.

2. CONFUSION IN THE MID- AND FAR- INFRARED

2.1. *Confusion of Extragalactic Sources at 24 μm*

The available measurements extend well into the extragalactic confusion regime at 24μm, and the detector performance is also well understood even for long integrations. Therefore, we use this band to develop the general principles applicable to determining the confusion limits in *Spitzer* mid- and far-infrared imaging data.

2.1.1. *Confusion Limit Calculation*

Our confusion estimates are based on the methodology described by Dole et al. (2003). We have used the number counts determined by Papovich et al. (2004), extrapolated to fainter flux limits according to the model of Lagache et al. (2004). Because these counts indicate that the background will be largely resolved into individual sources, the appropriate measure of the confusion is the SDC. We obtain 56 μJy for the 5-σ confusion level, corresponding to 12 beams per source. It appears that this confusion level is in perfect agreement with the 5σ pre-launch predictions of Xu et al. (2001), even if it was derived differently. If it were limited by photon noise only, the instrument would reach a detection limit of 56 μJy 5-σ in 1900 seconds of integration (Rieke et al. 2004), so the model predicts that the gain in signal to noise ratio will have leveled out significantly for integrations of this length.
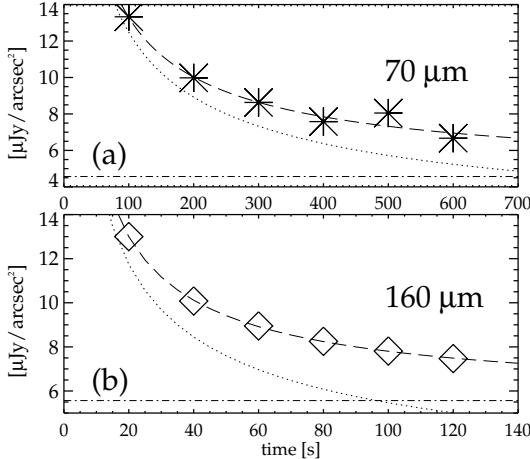
FIG. 1.— Evolution of σ_{tot} (resulting contribution from the confusion noise and instrument noise, and derived from the Gaussian fit in the brightness map pixel histogram) as a function of integration time, with a fit (dash) of the form: $\sigma_{tot}^2 = \sigma_{inst}^2 + \sigma_{confBr}^2 = At^{-1} + C^2$. Dot-dash: constant term C. Dot: $\sqrt{A/t}$ term. Top panel (a): 70 μm. Middle panel (b): 160 μm. Notice the different scales in time (seconds) and σ_{tot} (in brightness μJy/arcsec^2).

There is excellent agreement between the observed 80% completeness level and source density of Papovich et al. (2004), and our SDC confusion level. However, it should be possible in principle to integrate below the 56 μJy level, on a *selected field* of very low source density. In the "GOODS Test Field" in ELAIS N1 (described in Papovich et al. 2004), we estimate the area suitable for a deeper integration to be about 5% of the field area.

2.1.2. *Noise Analysis*

We desired a test of these predictions that was as much as possible independent of assumptions about the infrared galaxy population. For this purpose, we have characterized the noise in the 24 μm data from the ELAIS N1 field, the deepest observation obtained to date at this wavelength. We selected a very cleanly reduced region in the field, about 2 x 4 arcmin in size. We prepared two versions of the image in this region, both reduced identically, but one with an integration of 630 seconds and the other with an integration of 3800 seconds. We determined the pixel signal histogram in two ways. 1.) On a small region that also appeared to be free of detected sources, we verified that the standard deviation as measured in these histograms scaled inversely with the square root of the integration time. 2.) On the entire 2 x 4 arcmin region, we fitted it with a Gaussian of width fixed to the expectation for detector/photon noise. We required this Gaussian to fit only the negative side of the histogram, on the assumption that there were no negative sources. We took the departure of the measured histogram from this fit toward positive fluctuations to be the influence of (at least) sources in the field. We measured the extension of the distribution toward positive values at half maximum. We found that the positive-going width of the distribution was larger than the pure detector/photon noise expectation by a factor of 1.7, in qualitative agreement with the effects of confusion. These excess fluctuations likely result from a combined effect of extragalactic sources, faint cirrus and

TABLE 1
Spitzer MIPS CONFUSION LEVELS[a]

	24 μm [μJy]	70 μm [mJy]	160 μm [mJy]
SDC[b]	56	3.2	40
20b[c]	71	3.5	45
40b[d]	141	6.3	63
Phot[e]	8	0.7	45

NOTE. — (a) with Lagache et al. (2004) model. (b) Using the Source Density criterion (Dole et al. 2003). (c) Using the flux corresponding to one source per 20 beams. (d) Using the flux corresponding to one source per 40 beams. (e) Using the standard photometric criterion and $q = 4$, for illustration.

zodiacal light gradient. It is not clear at this stage which component dominates the fluctuations.

2.1.3. *Monte Carlo Simulation*

To empirically quantify the effect of confusion, we carried out a Monte Carlo simulation of source extraction under the conditions appropriate for the *Spitzer* deep 24μm exposures. The approach is described in detail by Rieke et al. (1995). We built up a test field by distributing confusing sources randomly according to a power law distribution matching the faint *Spitzer* number counts. Each source was entered as an Airy pattern. A test source of known amplitude was added to the center of the array, along with Gaussian noise. The sources were then identified using a modified CLEAN algorithm and finally the signal to noise was measured in a master array built up from the results of the CLEAN process, and in extraction apertures of various sizes. An important aspect of this simulation is that it combines the effects of neighboring bright sources and of the underlying, unresolved distribution of faint ones, in a consistent manner. It should give a good measure of the confusion noise independent of the division between source density and photometric criteria.

In the simulation, we excluded all objects brighter than 400μJy to avoid undo noise from bright-source artifacts. The first set of runs tested the extraction of a 56μJy source in an 0.8 λ/D beam, the beam size previously indicated to provide optimum performance in a heavily confusion-limited situation (Rieke et al. 1995 - this result was confirmed by the new calculations). We made 1200 runs for an integration time long enough to drive detector/photon noise down to 12.5μJy, 5-σ. They yielded a net 5-σ limit of 60μJy: removing the detector/photon noise leaves 59μJy of confusion noise. That is, this approach agrees well with the SDC-determined limit of 56μJy.

We also simulated the results to be expected from shorter integration times. For example, if the 5-σ detector/photon noise limit was set to 65μJy, then the indicated 5-σ level of confusion noise was 76μJy, significantly poorer than from the simulation of very long integrations. This effect probably results from the increased uncertainty in source centroiding and the resulting lower accuracy in extracting accurate source measurements from a confused field. To test this hypothesis further, we sim-

ulated extraction of a 36μJy source in the high signal-to-noise integration case, and found that the indicated 5-σ confusion limit rose to 64μJy, confirming the effect.

2.2. *Confusion by Extragalactic Sources at 70 μm*

At 70 μm, we again use the number counts (Dole et al. 2004) as the basic input to determining the confusion level. The updated model of Lagache et al. (2004) was used to extrapolate the counts and to derive updated confusion limits. The use of a model is critical in this case because the contribution of unresolved sources is not negligible. We derive a confusion level at 70 μm of 3.2 mJy using the SDC (Table 1). The differential source counts are almost flat (when divided by the Euclidean component), and the contribution from unresolved sources is much smaller than that of the resolved sources. These results demonstrate that the SDC estimate is the appropriate one, that is, the confusion is dominated by faint resolved sources rather than the unresolved background due to even fainter objects. Further details are given in Table 1. From the instrument radiometric model, we estimate that about 1800 seconds of integration would be required to reach this limit.

Again, we sought to check these results by a pure fluctuation analysis on the data without referring to galaxy population models. We used the data described by Dole et al. (2004) for the Chandra Deep Field South. We determined the evolution of σ_{tot}, the standard deviation of a Gaussian fitted to the surface brightness distribution as a check of the results from extrapolating number counts downward. Data were combined into 6 mosaics corresponding to 100s to 600s integration time per sky pixel with 100s steps. Figure 1a shows the evolution of σ_{tot70} with time. We do not observe substantial flattening in the σ_{tot70} time evolution. We conclude that MIPS 70 μm surveys do not reach yet the confusion limit after 600s of integration. An estimate of the confusion level is given by fitting the time evolution of σ_{tot70}. We find that the detector/photon noise will be roughly equal to the confusion noise at ≥ 800 seconds of integration, with large uncertainties because the fluctuation curve is still dropping almost as the square root of the integration time at the longest integration available. As at 24μm, this result is in satisfactory agreement with the integration time predicted by the SDC modeling.

2.3. *Confusion by Extragalactic Sources at 160 μm*

The data used at 160 μm are also described by Dole et al. (2004). The Lagache et al. (2004) model predicts a confusion level of 40 mJy (Table 1). From the instrument radiometric model, we estimate that about 70 seconds of integration would be required to reduce the instrument and photon noise to the level of the confusion noise.

A similar fluctuation analysis as at 70 μm was conducted at 160 μm, where 6 mosaics corresponding to integration times of 20 to 120s (with 20s steps) were studied. Analyzing the fluctuations is more difficult in this case since bright sources in the Euclidean regime contaminate the statistics, and since the map S/N is not uniform. Nevertheless, we estimate from Figure 1b that the confusion and detector/photon noise should be equal at about 95 seconds of integration, in good agreement with the result from the SDC analysis.
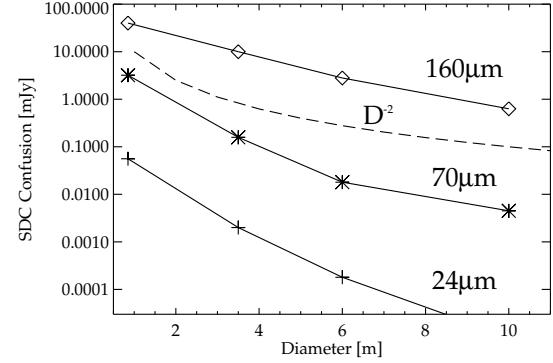
FIG. 2.— Confusion level vs Telescope Diameter, predicted by the Source Density Criterion (Dole et al. 2003) with the updated model of Lagache et al. (2004), at 24 (plus), 70 (star) and 160 μm (diamond). Diameters refer to *Spitzer*, Herschel and SPICA, JWST and SAFIR. Dash: inverse square diameter law shown for illustration.

2.4. *Confusion by Galactic Cirrus*

Another sensitivity limitation arises due to the structure of the IR cirrus. To estimate how this cirrus emission may affect the source detectability, we compared the 80% completeness limit in sky regions characterized by different cirrus background levels, using simulations as described in Papovich et al. (2004). We used a dedicated engineering observation in Draco of a *bright cirrus*, of HI column density n_{HI} varying between 4 and $14 \times 10^{20} cm^{-2}$. At 24μm, we find a relatively weak effect, and derive a completeness degradation of 15% ($\sim 50\mu$Jy increase from 340μJy) between the dark and the bright parts of the cirrus field. The effects of cirrus are more conspicuous at 70μm. We reach a 80% completeness in Draco of ~17mJy and ~27mJy. In a low-cirrus field (e.g., Marano) and for a similar integration time (100s), this level drops at ~12mJy. We compared the estimates in Draco with those provided by the Performance Estimation Tool of the *Spitzer* Science Center and found that the measured value variations as a function of the cirrus strength are in general agreement (within 30%) with those estimated by the tool from low to medium background. This comparison will be refined as we continue to acquire far-infrared data.

3. IMPLICATIONS FOR FUTURE OBSERVATORIES

A number of cryogenically-cooled space telescopes have been proposed for the MIR, the FIR and the submillimeter spectral ranges. Table 2 summarizes the main characteristics of some of these observatories. Herschel (Pilbratt 2001), JWST (Gardner 2003), SPICA (Matsumoto 2003) and SAFIR (Yorke et al. 2002), have at least one photometric channel in common with MIPS. As examples, we focus on Herschel-PACS at 75 and 170 μm, on JWST-MIRI at 24 μm, and on SPICA and SAFIR at 24, 70 and 160 μm, assuming in each case that the MIPS filters will be used.

For each of these observatories, we compute predictions for the confusion level for unbiased surveys using the Lagache et al. (2004) model of source counts. We assume a Gaussian beam profile for these future observatories, with a FWHM of $1.22\lambda/D$, λ being the wave-